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The Application of Drop-on-Demand Ink Jet Technology to Color Printing

The application of drop-on-demand ink jet technology to high-frequency and high-resolution color printing is investigated using an experimental multi-nozzle print head. Cross talk and drop misregistration are examined as a function of drop ejection frequency. Typical print samples from scanned and computer-generated data are obtained and the dependence of print quality on various parameters such as drop ejection frequency, ink composition, and paper quality is discussed.

Introduction

The use of ink jet technology for printing of alphanumeric information was first investigated by Sweet [1]. Using an ink reservoir under high pressure and a piezoelectric crystal upstream from a small orifice, Sweet created a sequence of small droplets which could be deflected electrostatically according to their charge during their passage through high-voltage deflection electrodes. This principle of drop generation has been used in a number of commercial printers, such as, for instance, the Mead multi-jet line printer [2] and the IBM 6640 ink jet printer.

In recent years, electrostatic ink jet technology has been applied to color printing and several products or prototypes of color printers are presently available [3-5]. High-density color images have been reported at a density of 40 pels/mm (1000 pels/in.) by Yamada et al. [6] and at a density of approximately 20 pels/mm (500 pels/in.) by Crooks et al. [7]. Although used successfully in the above applications, several problems exist that make the application of electrostatic ink jet technology very cumbersome. First, the ejection of a continuous sequence of drops implies that all drops not needed for printing must be deflected into a gutter without striking the paper. This "surplus" ink must then be filtered and recirculated to the ink supply, a process which is difficult to implement in a color printer and requires a substantial amount of additional hardware. Second, the requirement of constant pressure for driving the individual ink jets adds to

the complexity of the mechanical parts. In addition, the need for high-voltage deflection electrodes is cumbersome and can lead to arcing due to misplaced ink droplets.

The so-called "drop-on-demand" ink jet method also uses small droplets of ink but only those drops are ejected which are needed for printing. As described in more detail elsewhere in this issue [8], the method is based on the generation of an acoustic wave in a fluid-filled piezoelectric transducer by the application of a voltage pulse. The acoustic wave interacts with the free meniscus surface at the nozzle to eject a single drop. Thus, drops are ejected only when needed for printing, and no ink recirculation or high-pressure source for the ink is necessary. Conceptually, the drop-on-demand method should be easier to implement than the electrostatic method, since it requires less hardware. On the other hand, since the drop ejection rate of drop-on-demand transducers is much lower than that of typical "continuous" ink jet transducers, a number of independent transducers must generally be used to achieve reasonable print speeds. The drop-on-demand method has been studied extensively in the past years [9-11], and several low-resolution printers based on the use of that method have been developed for black and white as well as color printing [12-15].

In this paper, we describe attempts to use an experimental multi-nozzle drop-on-demand print head to achieve high-

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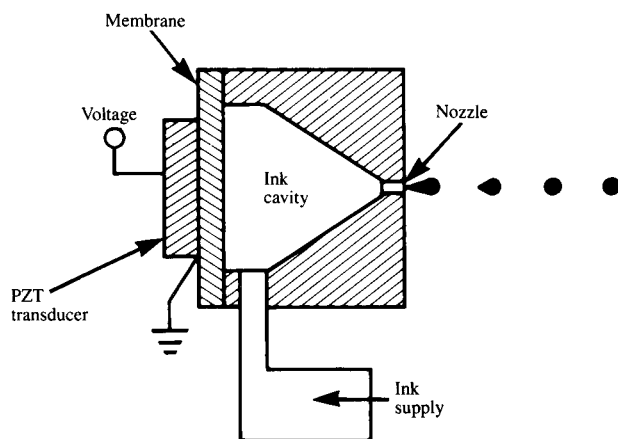


Figure 1 Two typical single-nozzle drop-on-demand drop generators.

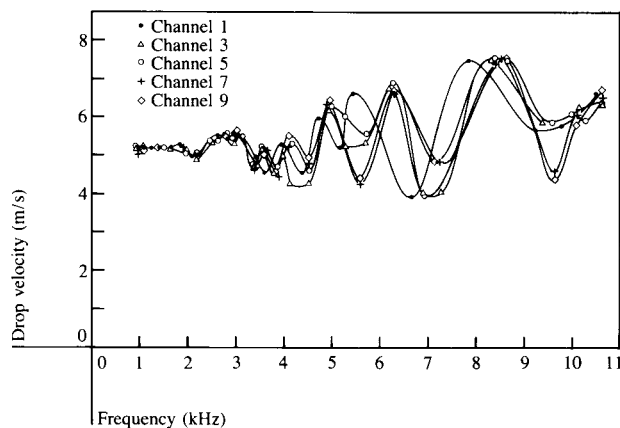


Figure 3 Frequency response for typical channels of the experimental multi-nozzle print head.

frequency and high-resolution color printing. Typical print samples from scanned and computer-generated data are presented, and the dependence of print quality on various parameters such as frequency of drop-generation, ink composition, and paper quality is discussed.

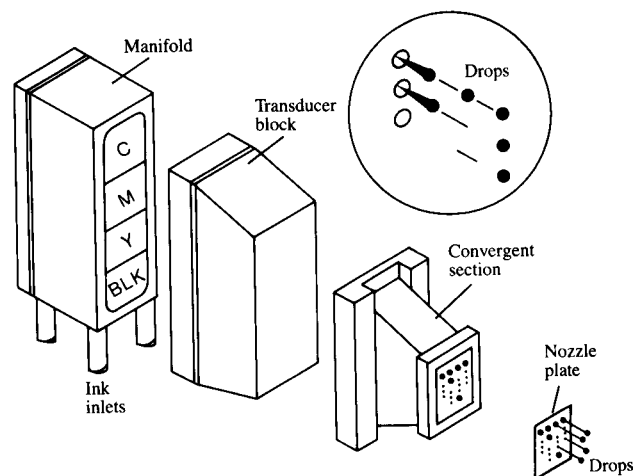


Figure 2 Schematic view of experimental multi-nozzle print head.

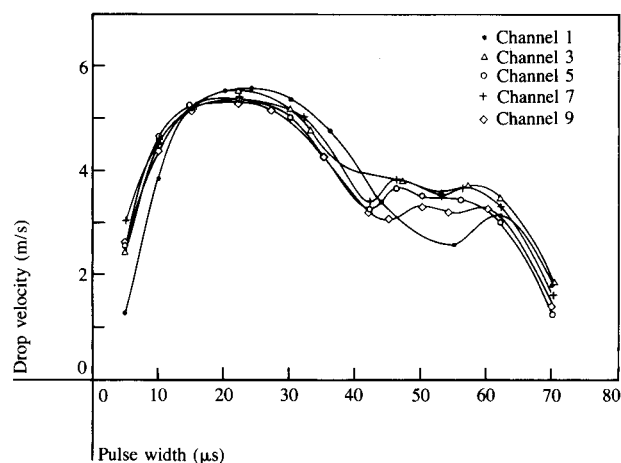


Figure 4 Drop velocity vs. pulse width for typical channels of the experimental multi-nozzle print head.

Single-nozzle drop-on-demand drop generators

In **Figure 1**, we show two typical single-nozzle drop-on-demand drop generators [16]. In each case, the drop generator consists of an ink-filled cavity that is adjacent to or surrounded by a piezoelectric transducer (PZT). The front of each cavity contains a small orifice through which the ink droplets are ejected. Upstream from the nozzle is an ink inlet which allows ink to enter the drop generator from the ink supply.

Requirements for color print head

For color printing, at least three drop generators are needed, i.e., one for each of the primary colors cyan, magenta, and yellow for subtractive color printing. Although the superposition of the three primary colors produces black, it is advantageous from the viewpoint of print quality and color mixing to have a separate drop generator for black ink. This results

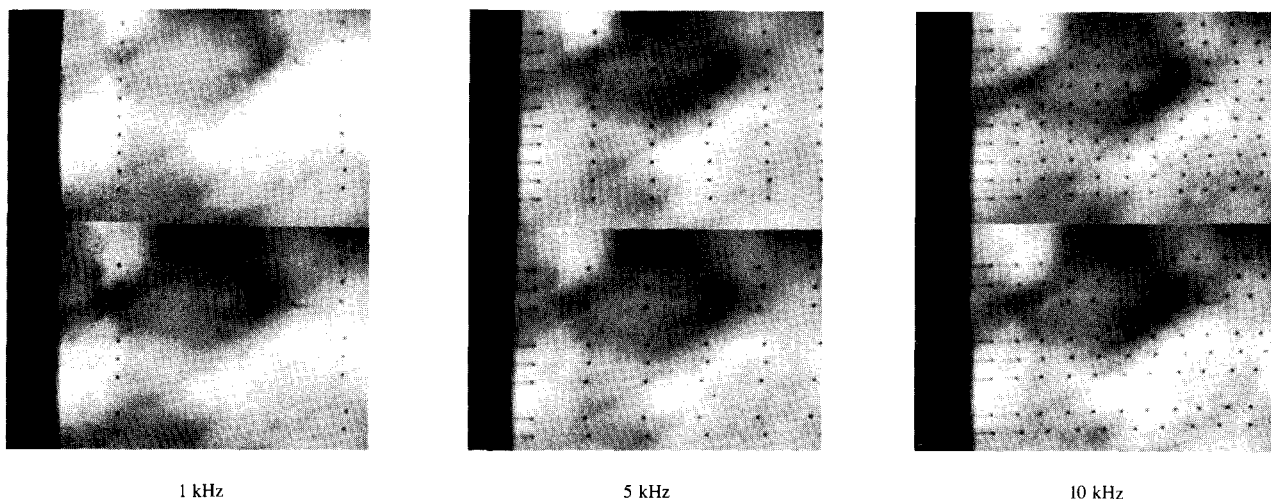


Figure 5 Drop placement at 1 kHz, 5 kHz, and 10 kHz for typical section of the experimental multi-nozzle print head.

in a four-color system: cyan, magenta, yellow, and black. Furthermore, in order to obtain adequate print speed, it is desirable to have more than one nozzle per color.

Description of multi-nozzle print head

In Figure 2, a schematic view of our experimental multi-nozzle print head is shown. It consists of four columns of nozzles and is divided in such a way that each of the primary colors corresponds to one of the columns of nozzles. The head is divided into the manifold section, the transducer section, and the nozzle plate section. The nozzle-to-nozzle spacing within one column is approximately 0.4 mm (16.7 mils). In order to achieve a higher density than 2.4 dots/mm (60 pels/in.), microstepping of the paper must be implemented. For most of our investigations, we have printed at 9.5 dots/mm (240 pels/in.), which requires three microsteps of the paper prior to a line feed.

Frequency response of the multi-nozzle print head

To achieve accurate drop placement and high print quality, it is desirable that all drops ejected from the multi-nozzle print head have the same velocity independent of frequency. In Figure 3 we show the frequency response in terms of drop velocity vs. frequency for several channels of the experimental print head. We observe that the velocity is constant only at very low frequencies. As the drop ejection frequency increases, the velocity of the individual channels deviates by increasingly larger amounts from the nominal value. However, the velocity variation is similar in all channels as a function of frequency and remains within ± 30 percent of its nominal value at 1 kHz.

The drop velocity variation at high frequency is caused by the interaction of the acoustic waves that eject a drop at a

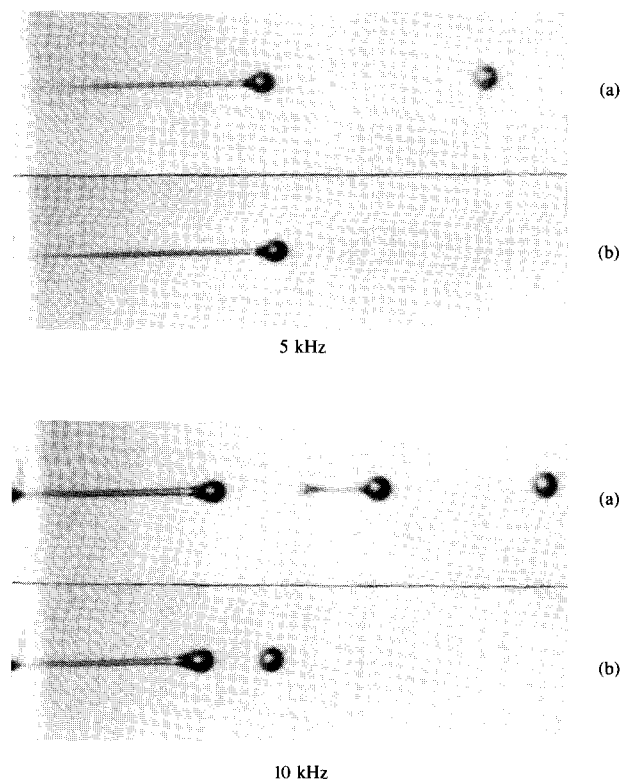


Figure 6 Drop placement in a single stream. Synchronous drop-ejection condition is depicted in the "(a)" sequences; asynchronous drop-ejection condition is depicted in the "(b)" sequences.

time t , and the reflected acoustic waves from the ejection of all previous drops. If the time period between two successive drops is large enough, the reflected waves are damped out completely prior to the ejection of a new drop and the drop

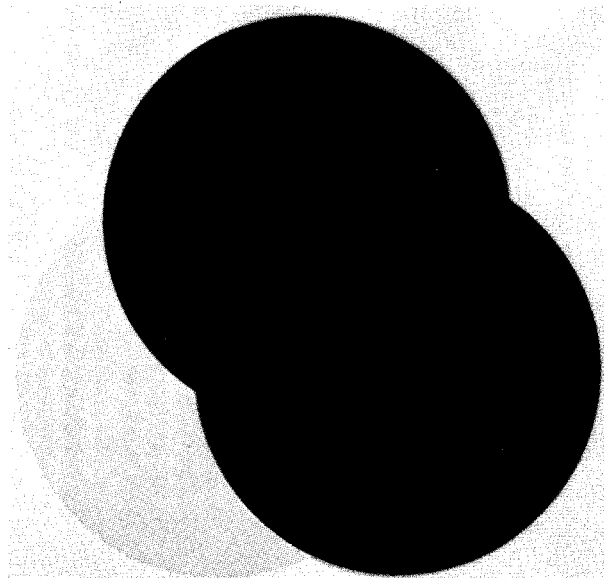


Figure 7 Subtractive color scheme (reduced photograph of image printed at 240 pels/in. density).

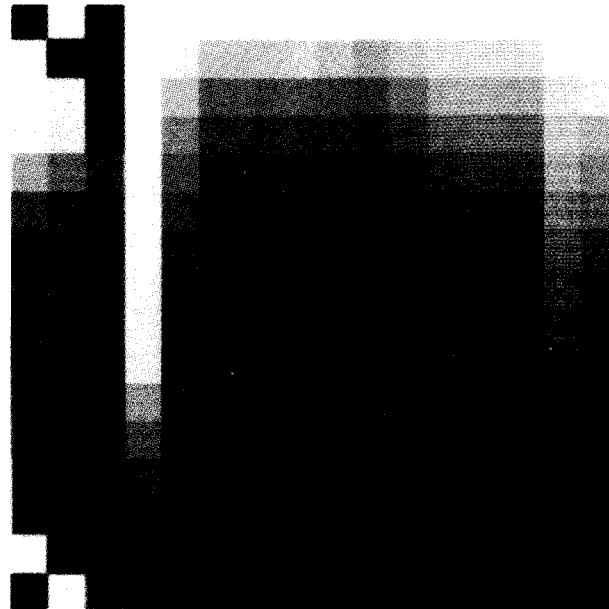


Figure 8 Color shades and hues (reduced photograph of image printed at 240 pels/in. density).



Figure 9 Print samples of scanned images (reduced photographs of images printed at 240 pels/in. density).



velocity is constant. With increasing frequency, the period between successive drops is shortened and the reflected waves within the fluid channel are not damped out completely prior to the ejection of the next drop. Thus, depending on the timing between the reflected waves and the wave causing ejection of the next drop, constructive or destructive interference occurs; the latter accounts for the peaks and valleys in the frequency response. In **Figure 4** the drop velocity of several channels is shown as a function of pulse width. As in Fig. 3, the channels display approximately the same variation of velocity with pulse width.

Cross talk

Cross talk may result from several effects. If a drop in a particular channel is eliminated during asynchronous printing, changes in the drop velocity of adjacent channels may occur

due to the nonuniform flow and pressure conditions in different channels. In addition, the velocity of drops following a deleted drop may deviate from the nominal value due to the acoustic wave interactions discussed above. Both of these velocity changes result in drop misregistration and cause a degradation in print quality. To avoid such print degradation, acoustic isolation and damping of the individual channels is important. Acoustic isolation requires consideration of the material used for the print head, the physical separation between channels, and the dimension and design of the channels and reservoir. Damping is primarily a function of the viscosity of the ink and the acoustic termination of the individual channels.

In **Figure 5**, we show the drop placement in a section of the print head at frequencies of 1 kHz, 5 kHz and 10 kHz,

respectively, after eliminating channels 3 and 7 from the bottom. There is no influence on the drop velocity in the adjacent channels in the 1-kHz case, while a velocity variation of less than ten percent is observed at 5 kHz and 10 kHz, respectively. In Figure 6, we show the drop placement for a single channel at 5 kHz and 10 kHz, respectively. For the sequences denoted by an "(a)," synchronous conditions were used for drop ejection; for those denoted by a "(b)," asynchronous conditions were used which caused the elimination of the leading drop in each sequence. We note that the velocity of the drop following the "missing drop" is much more affected at 10 kHz than at 5 kHz.

Data path for color information

In order to print color information with the multi-nozzle print head, bit maps must be created for each primary color. Two ways exist to achieve this. First, we can create bit maps by scanning an original color photograph or picture with three separate filters, reformatting these data for our print head, and then feeding the data "in parallel" to the print head after using image enhancement algorithms [17]. Since scanning gives analog amplitude information for each primary color, conversion of the scanned data into binary information is necessary. The second way to obtain bit maps for our color head is to use graphic routines, numerical calculations, or interactive terminal displays such as the IBM 3279 or the color monitor of a personal computer. In the latter case, the bit maps are best obtained by conversion of vector information to raster data; i.e., the bit maps that are generated can be obtained at any arbitrary resolution. Thus, enlargement or reduction of graphical output is easily possible.

Subtractive color scheme for color printing

From the primary colors cyan, magenta, and yellow, we can obtain the secondary colors red, green, and blue, by the superposition of magenta and yellow, cyan and yellow, and magenta and cyan, respectively (Figure 7). Since black is available as a separate color, we are thus able to print with seven individual colors. To generate various other color shades and hues, computer-controlled algorithms are used, as for example in Figure 8.

Print samples

In Figure 9, we show two print samples of scanned data, obtained at a density of 9.5 lines/mm (240 pels/in.) and a print frequency of 5 kHz. In Figure 10, we show two print samples of computer-generated graphics at 9.5 lines/mm and print frequencies of 5 kHz and 10 kHz, respectively.

Discussion

The original print samples shown in Figs. 7-10 were obtained using commonly available short-fiber paper. This paper exhibits short drying time and adequate spreading of the ink. We have observed that drying time, print quality, and color



Figure 10 Print samples of computer-generated graphics (reduced photographs of images printed at 240 pels/in. density).

matching are influenced by the type of paper which is used. In Figure 11, we show the color hue and saturation for two paper types using the standard GATF color circle [17]. Clearly, substantial changes in color saturation are observed. The dyes and inks used for printing have a strong influence on color quality. Generally speaking, there are two types of ink that can be used, namely solvent-based ink and water-based ink. Since the viscosity of water-based ink is generally lower than that of solvent-based ink, shorter drying times and better print quality are to be expected with water-based ink. Other factors such as surface tension and the desire to minimize print head maintenance are also important. Clearly, careful consideration

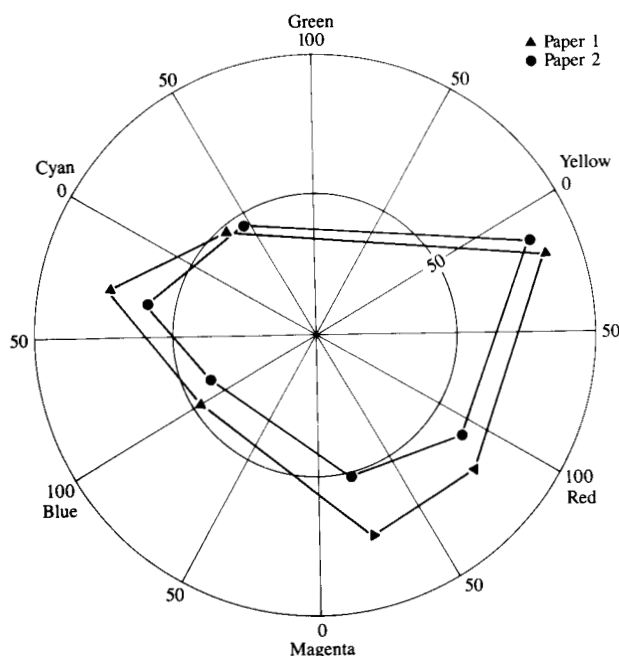


Figure 11 Standard GATF color circle for color saturation on two typical papers with same dyes.

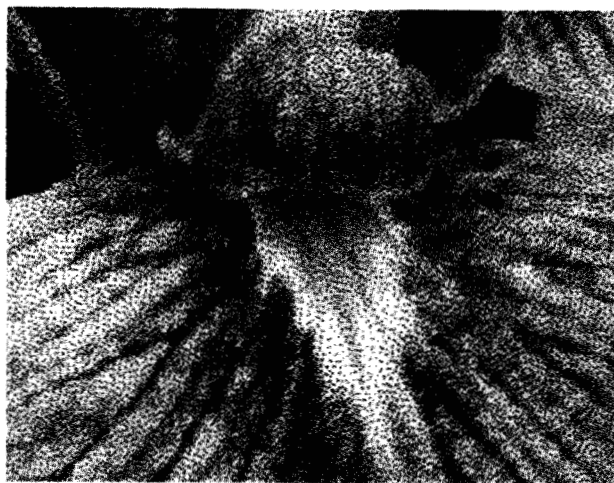


Figure 12 Blow-up of color image in left-hand portion of Fig. 9, showing drop misregistration.

must be given to all of the factors cited in this section in order to achieve satisfactory performance.

The color samples shown in Figs. 7–10 were printed at a density of 9.5 lines/mm. If a higher resolution is desired, a smaller drop diameter must be used; this can be achieved by decreasing the diameter of the nozzles. Conversely, lower-resolution printing may be achieved by increasing the spot size; this can be achieved by increasing the nozzle diameter.

It should be noted that pulse width and amplitude can also be used to change the drop diameter.

We discussed earlier that the print quality of color samples depends on drop placement accuracy, which in turn is a function of drop ejection frequency and cross talk. It should be noted that drop placement accuracy for printing of color images does not have to be quite as high as that for color graphics or high-resolution black printing, since the human eye seems to integrate the different color signals from the paper. This point is demonstrated clearly in **Figure 12**, which shows a blow-up of the left-hand image in Fig. 9. Although drops are misaligned by as much as 50 μm , the integrated effect of the colors is smooth and continuous to the human eye.

Summary

In this study we have examined the feasibility of high-resolution drop-on-demand color printing using an experimental multi-nozzle print head. Cross talk among channels was studied and found to be a function of frequency of drop ejection. Drop misregistration within a stream during asynchronous printing was also found to be a function of frequency. By devoting sufficient attention to print head design and operation, and ink and paper properties, images could be obtained which were nearly photographic in quality.

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